Tanta University

Faculty of Engineering

PROTECTION of ELECTRICAL POWER SYSTEMS

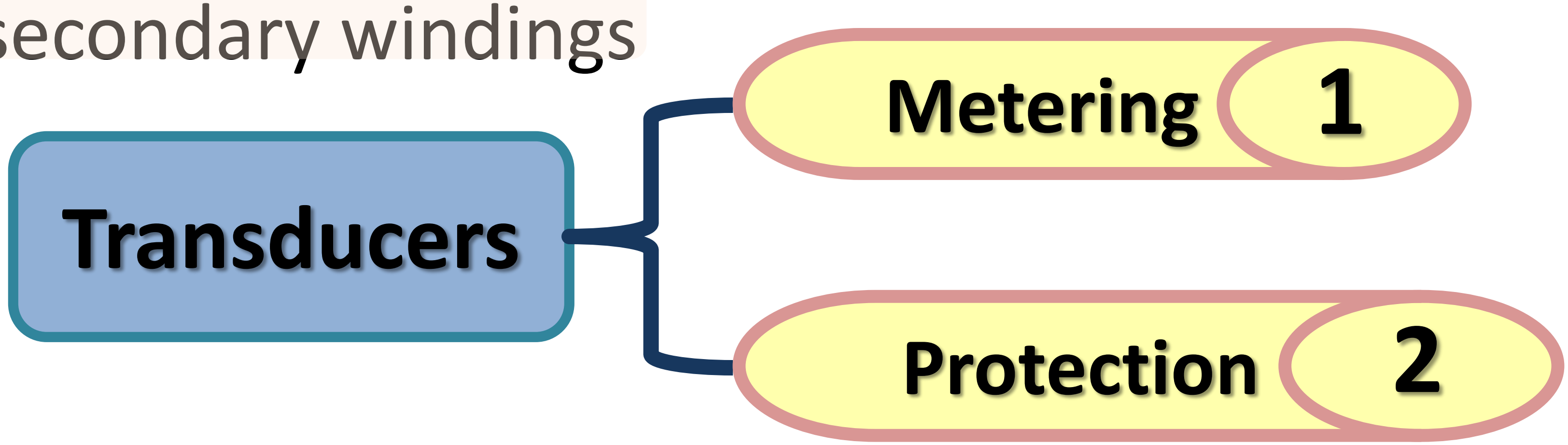
Current and Voltage Transformers

Dr. Hossam A. A. Saleh

Department of Elec. Power and Machines Eng.

Current and Voltage Transformers

- The function of current and voltage transformers is to transform power system currents and voltages to lower magnitudes, and to provide galvanic isolation between the power network and the relays and other instruments connected to the transducer secondary windings



Rating of Transducers Secondary Windings

For CTs

1 A or 5 A

For VTs

120 V LL

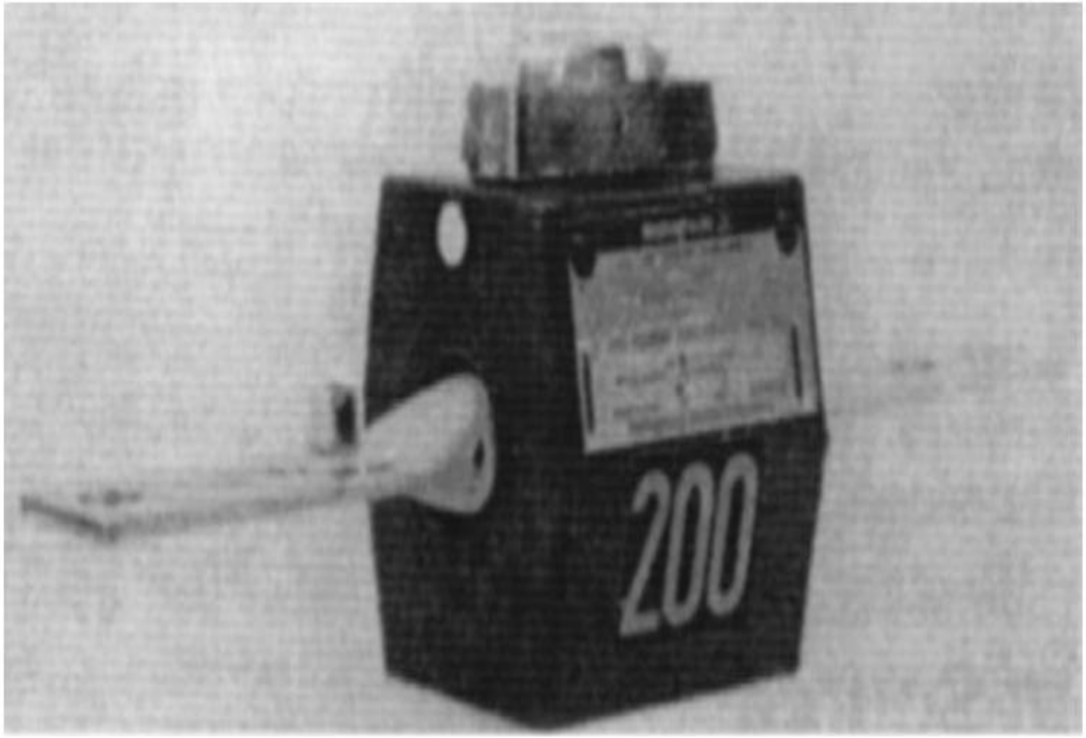
CTs are designed to withstand fault currents for a few seconds

VTs can withstand overvoltages (20% above the normal value)

Current Transformers

magnetically coupled, multi-winding transformers

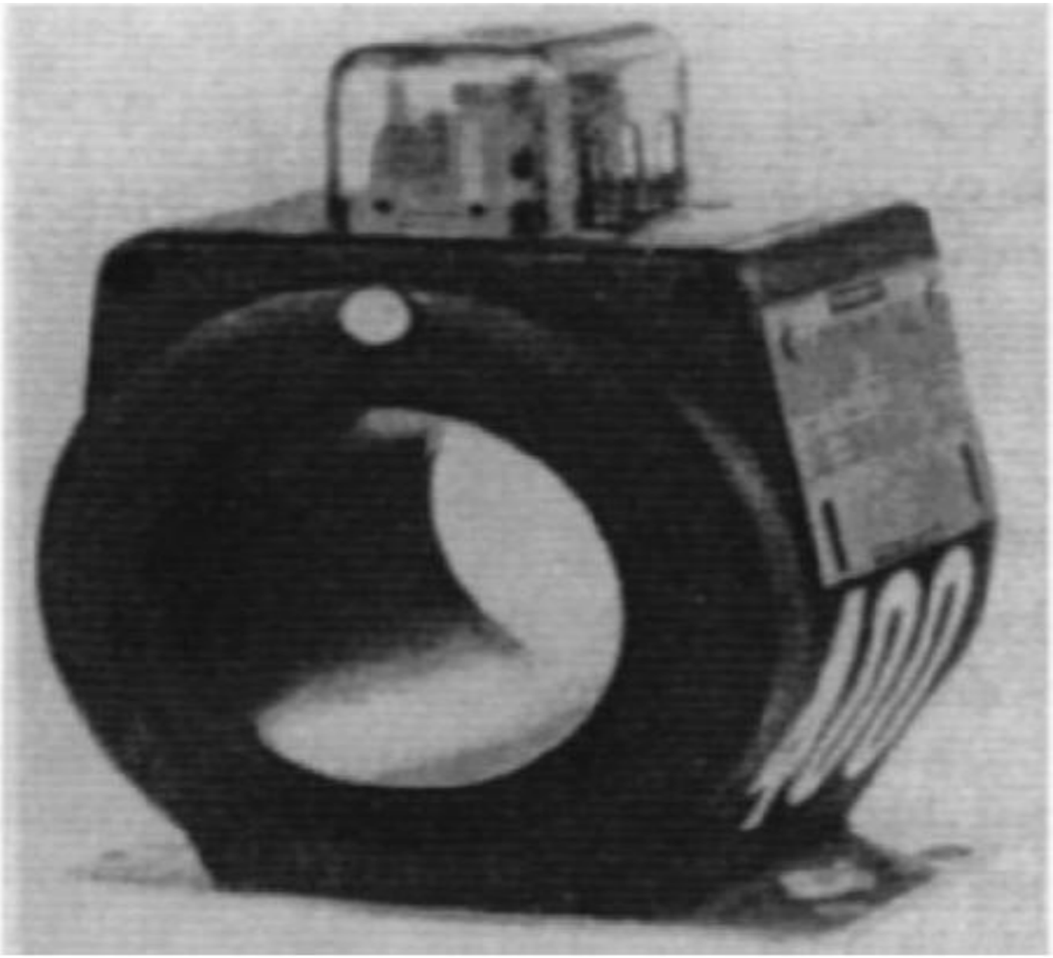
bar type



Current Transformers

magnetically coupled, multi-winding transformers

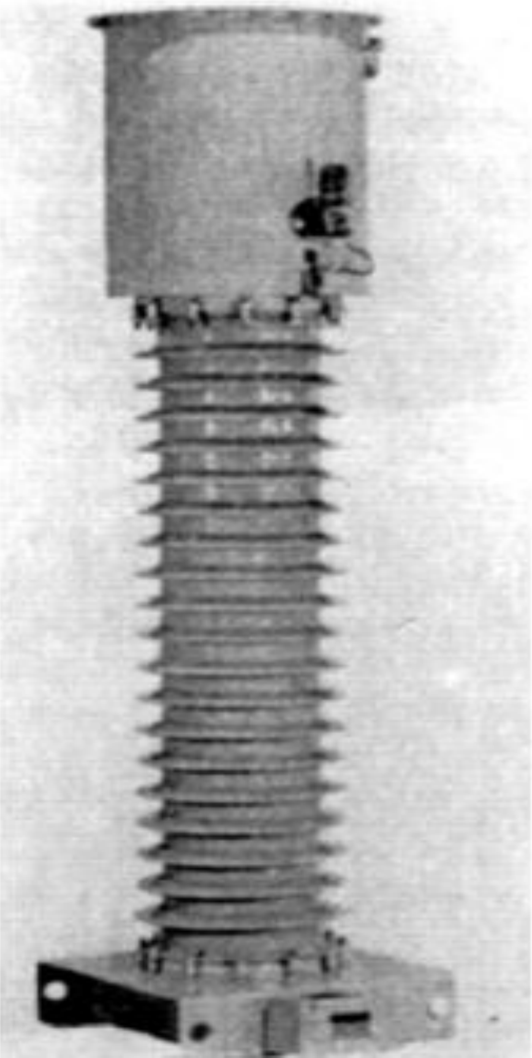
through-type



Current Transformers

magnetically coupled, multi-winding transformers

A 230 kV oil-filled CT



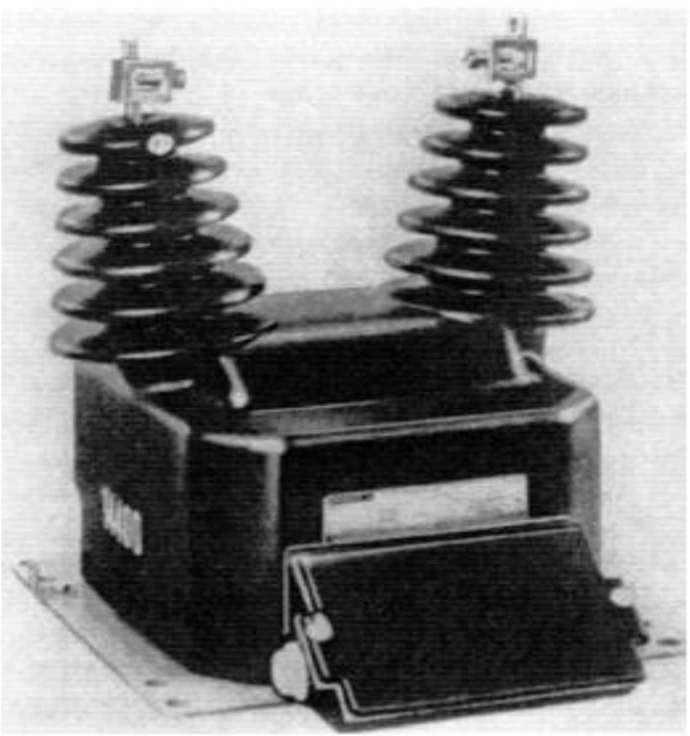

CB
CT


CT

Voltage Transformers

magnetically coupled

capacitive voltage divider

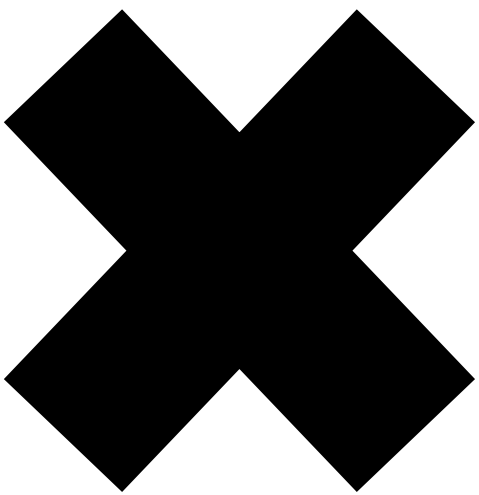


Low Voltage Systems

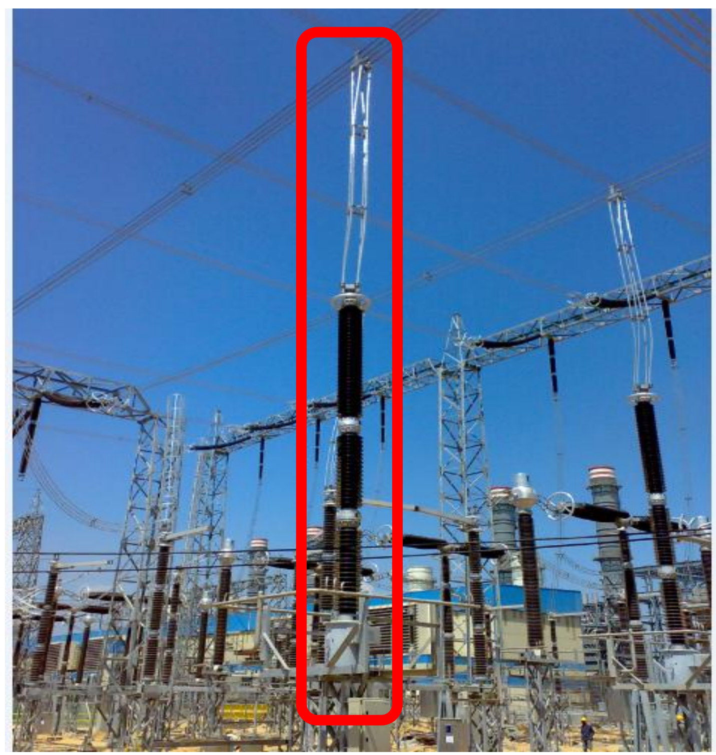
Voltage Transformers

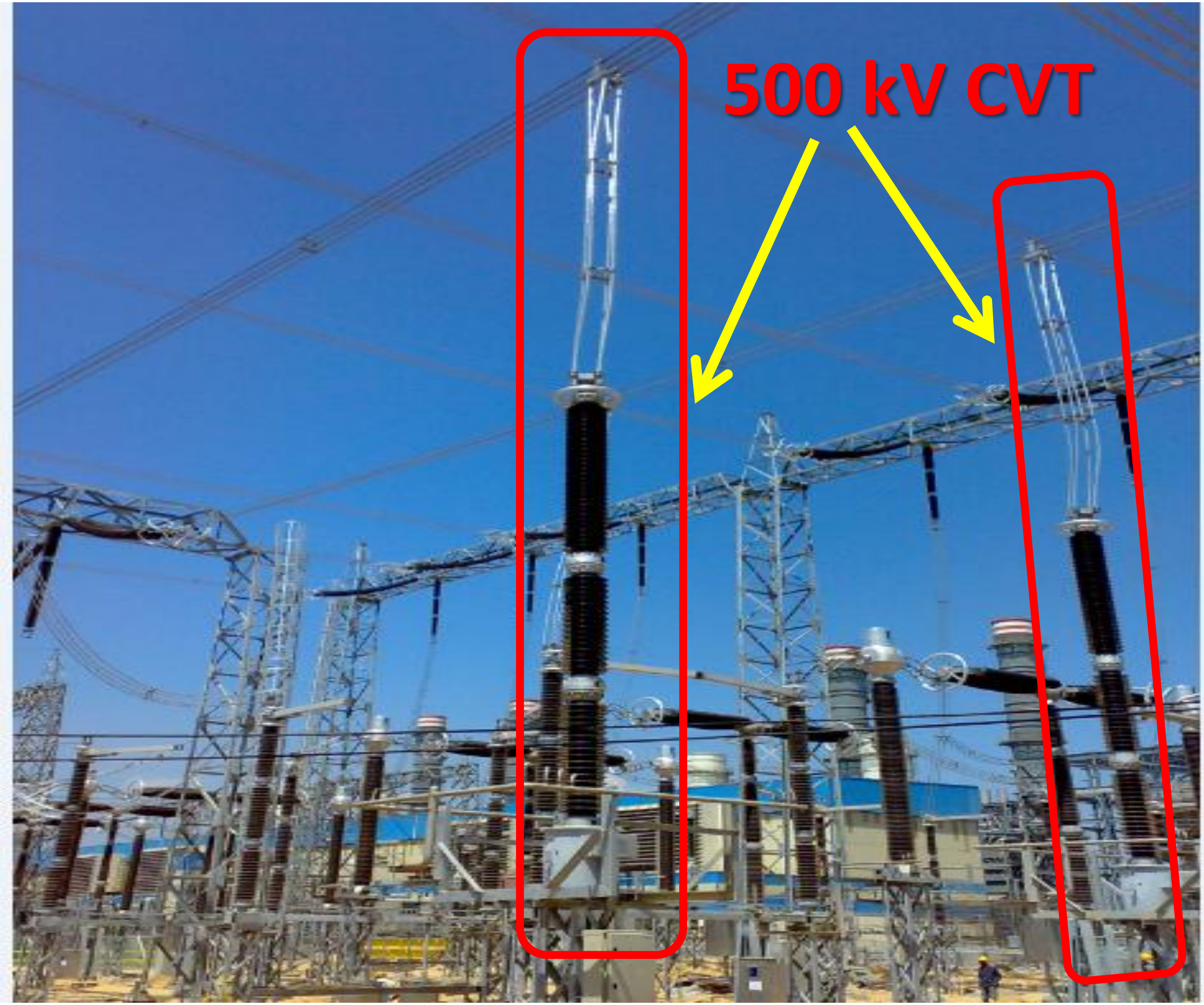
magnetically coupled

capacitive voltage divider



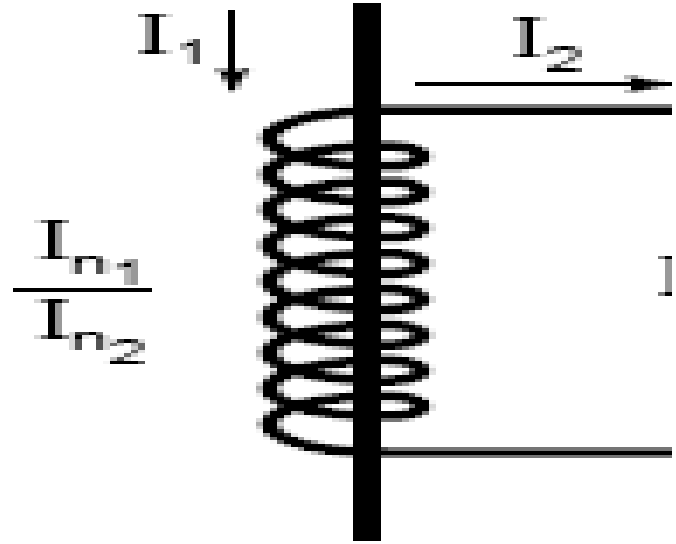
High Voltage Systems



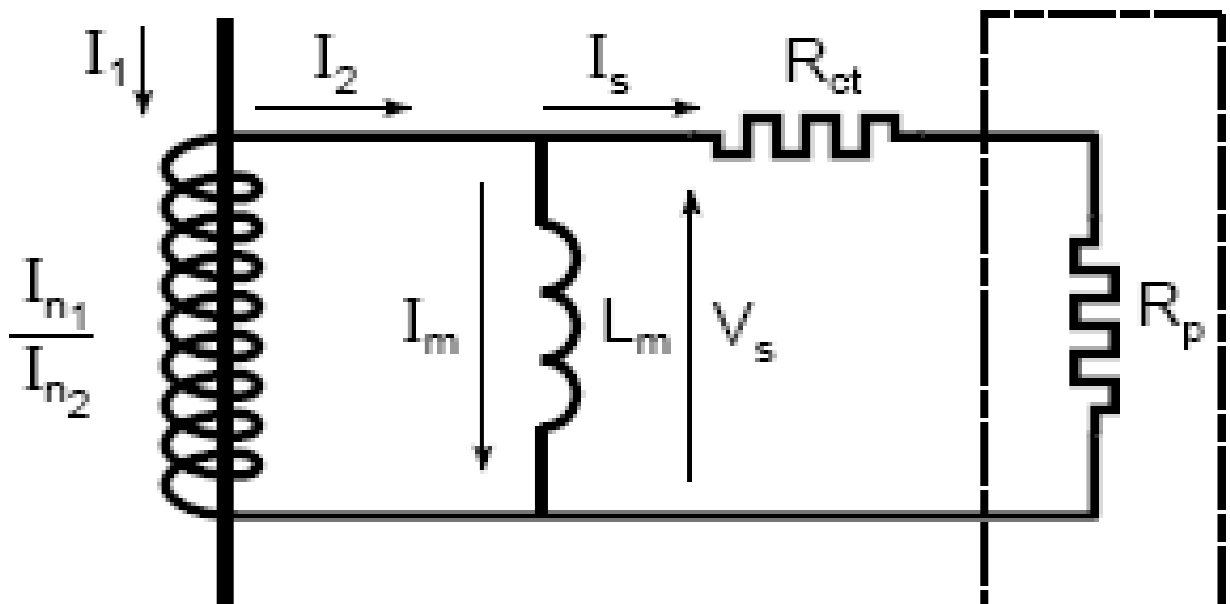

500 kV CVT

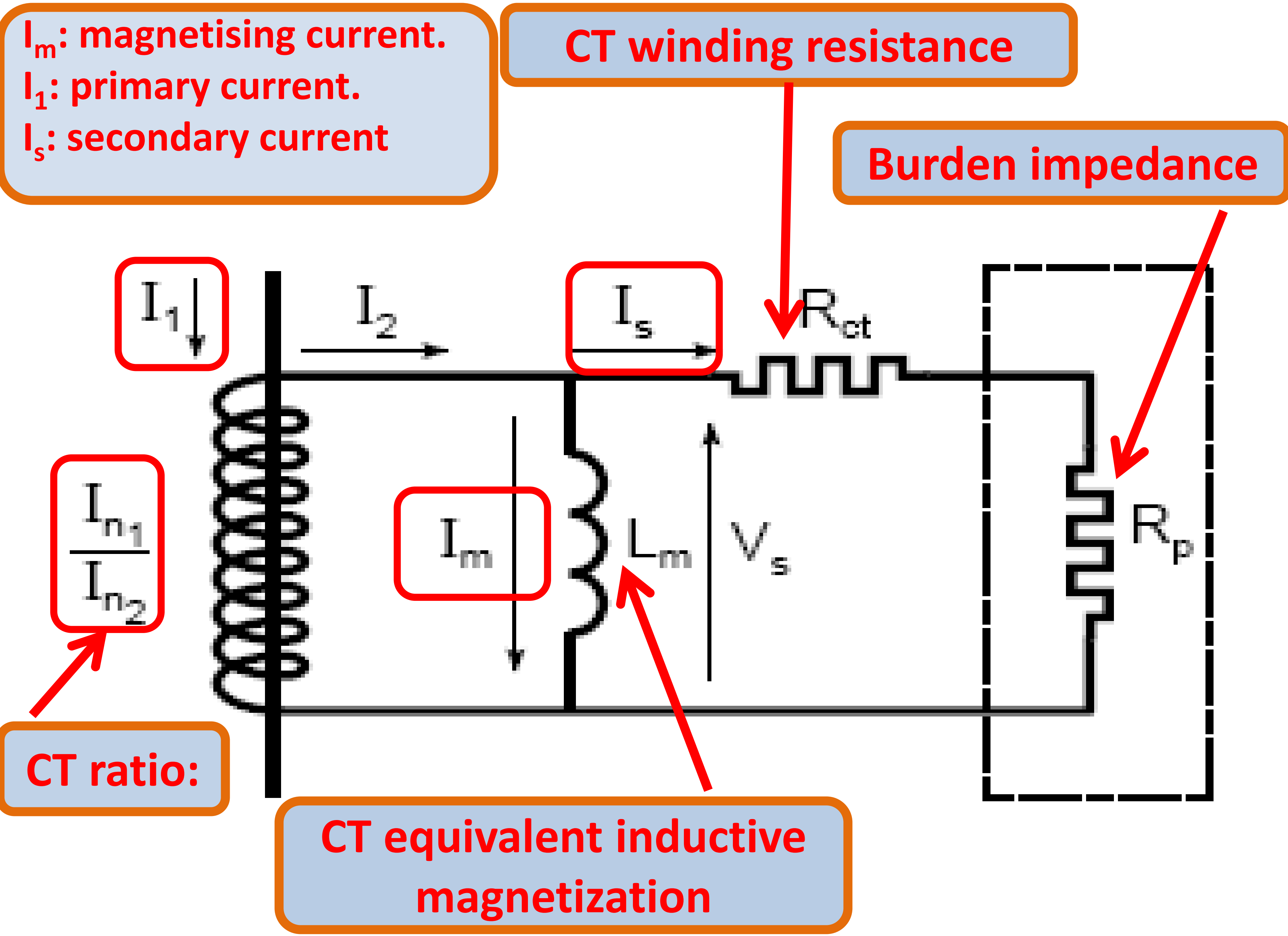
Steady-State Performance of Current Transformers

single primary, single secondary, magnetically coupled transformers



equivalent circuit





Im: magnetising current.
I1: primary current.
Is: secondary current
CT winding resistance
Burden impedance
I1
I2
Is
Rct
Im
Lm
Vs
Rp
In1
In2
CT ratio:
CT equivalent inductive magnetization

Burden Impedance Z_b

Impedance of all the relays and meters

+

Impedance of the leads from CT to these equipment

measured

<u>Ohm</u>

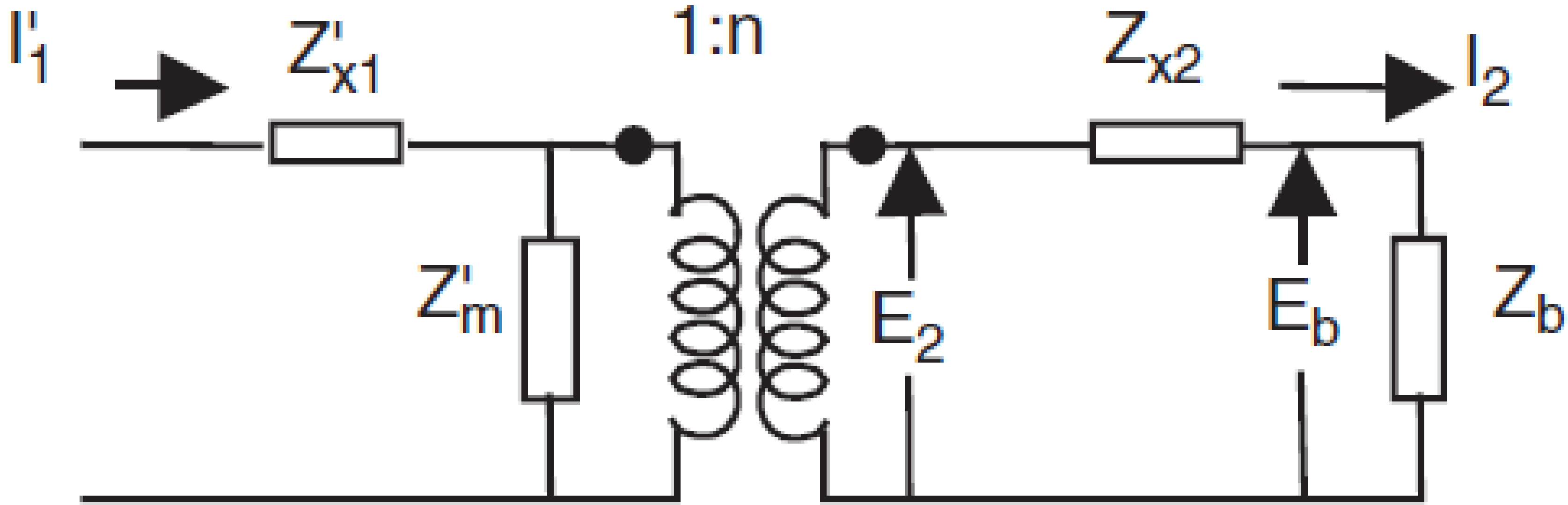
<u>VA</u>

Sum of all devices impedance

$25Z_b$

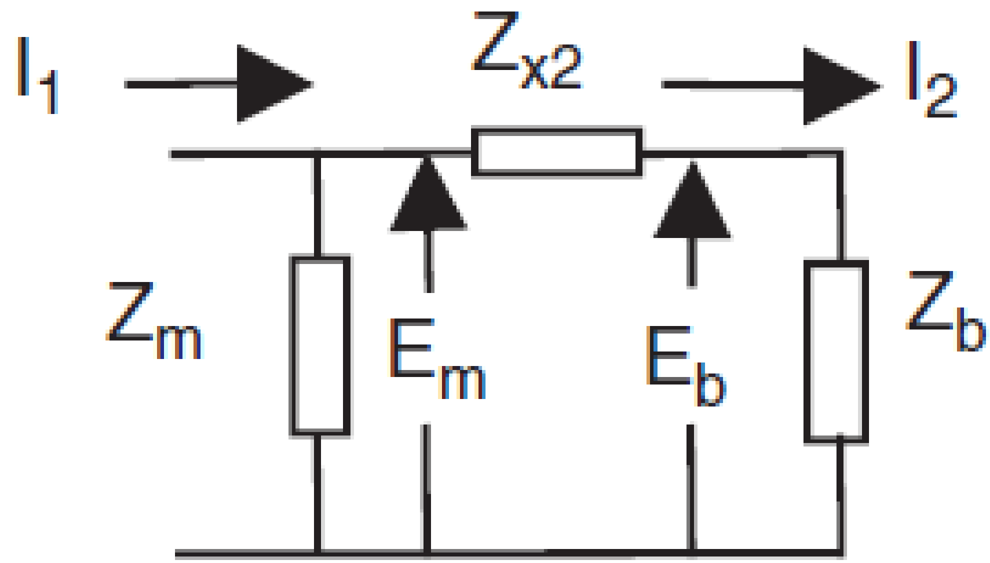
Or

Z_b

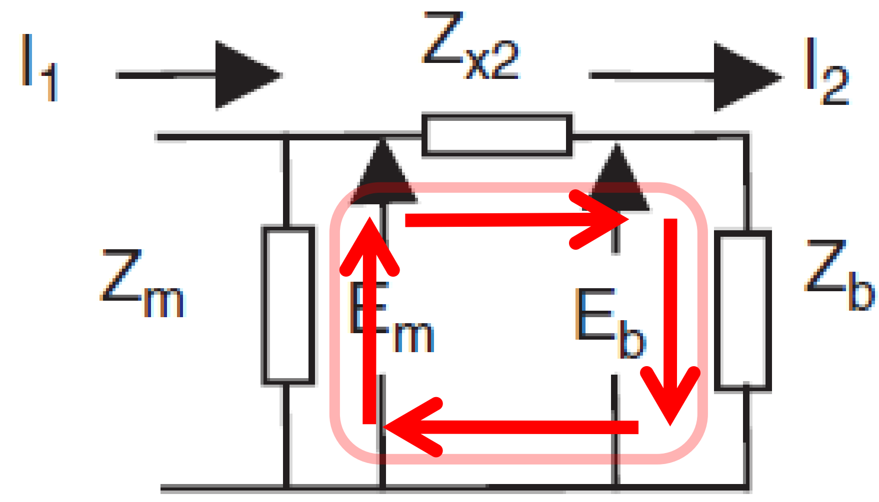


$$I_1 = \frac{I_1'}{n}$$

$$Z_{\mathrm{m}} = n^2 Z_{\mathrm{m}}'$$



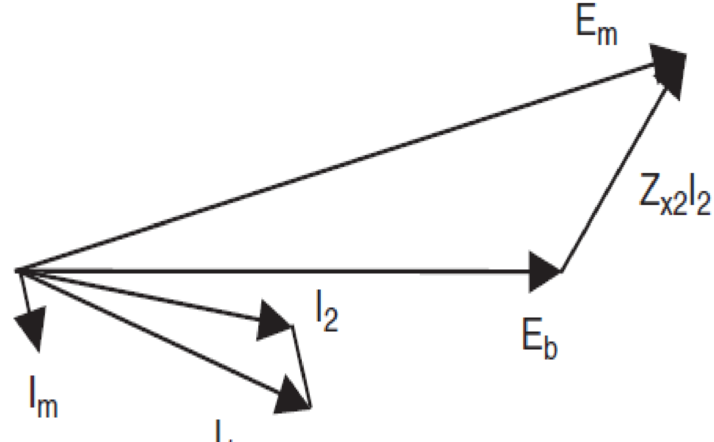
Apply KVL for loop 1



$$E_{\mathrm{m}} = E_{\mathrm{b}} + Z_{x2} I_2$$

$$I_{\mathrm{m}} = \frac{E_{\mathrm{m}}}{Z_{\mathrm{m}}}$$

$$I_1 = I_2 + I_{\mathrm{m}}$$



The per unit current transformation error defined by

$$\varepsilon = \frac{I_1 - I_2}{I_1} = \frac{I_{\mathrm{m}}}{I_1}$$

In ideal case of zero burden impedance, $I_1 = I_2$, and the CT error is zero.

Ratio Correction Factor *R*

is defined as the constant by which the name plate turns ratio *n* of a current transformer must be multiplied to obtain the effective turns ratio.

$$R = \frac{1}{1 - \varepsilon}$$

Although ε and *R* are complex numbers, it is sometimes necessary to use these values as real numbers equal to their respective magnitudes.

Example 1

Consider a CT with a turns ratio of 500:5, a secondary leakage impedance of (0.01 + j0.1) Ω and a resistive burden of 2.0 Ω. If the magnetizing impedance is (4.0 + j15) Ω. Determine *ε* and *R*.

For a primary current (referred to the secondary) of I_l

$$E_{\mathrm{m}} = \frac{I_1(0.01 + \mathrm{j}0.1 + 2.0)(4.0 + \mathrm{j}15.0)}{(0.01 + \mathrm{j}0.1 + 2.0 + 4.0 + \mathrm{j}15.0)} = I_1 \times 1.922\angle 9.62^\circ$$

and

$$I_{\mathrm{m}} = \frac{I_1 \times 1.922\angle 9.62^\circ}{(4.0 + \mathrm{j}15.0)} = I_1 \times 0.1238\angle -65.45^\circ$$

Thus, if the burden and the magnetizing impedances of the CT are constant, the per unit CT error

$$\varepsilon = \frac{I_m}{I_1} = 0.1238\angle -65.45^\circ$$

The ratio correction factor can be found as following:

$$R = \frac{1}{(1.0 - 0.1238\angle -65.45^\circ)} = 1.0468\angle -6.79^\circ$$

Z_b	ε	*R*
2 Ω	$0.1238\angle -65.45^\circ$	$1.0468\angle -6.79^\circ$
1 Ω	$0.064\angle -66^\circ$	$1.025\angle -3.44^\circ$
J2 Ω	$0.12\angle 12.92^\circ$	$1.13\angle 1.73^\circ$

ε and *R* factors depend upon the magnitude and phase angle of the burden and magnetizing impedances.

Since the magnetizing branch of a practical transformer is nonlinear, $\underline{Z_m}$ is not constant, and the actual excitation characteristic of the transformer must be taken into account in determining the factor *R* for a given situation.

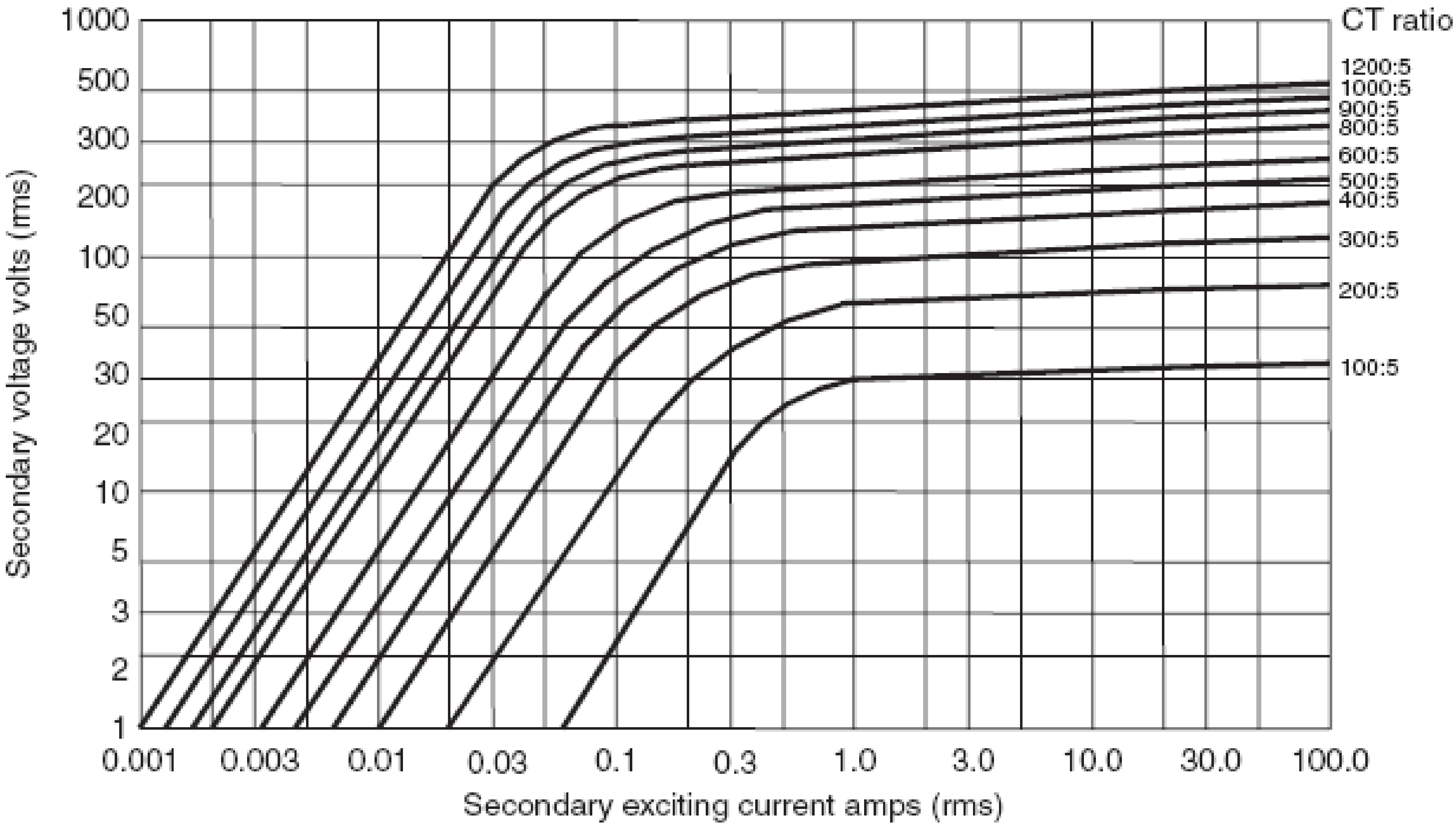


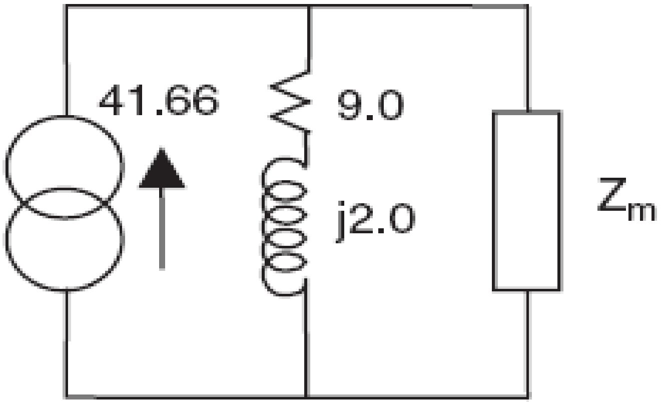
Table 3.1 Standard current transformer multiratios (MR represents multiratio CTs)

600 : 5 MR	1200 : 5 MR	2000 : 5 MR	3000 : 5 MR
50 : 5	100 : 5	300 : 5	300 : 5
100 : 5	200 : 5	400 : 5	500 : 5
150 : 5	300 : 5	500 : 5	800 : 5
200 : 5	400 : 5	800 : 5	1000 : 5
250 : 5	500 : 5	1100 : 5	1200 : 5
300 : 5	600 : 5	1200 : 5	1500 : 5
400 : 5	800 : 5	1500 : 5	2000 : 5
450 : 5	900 : 5	1600 : 5	2200 : 5
500 : 5	1000 : 5	2000 : 5	2500 : 5
600 : 5	1200 : 5		3000 : 5

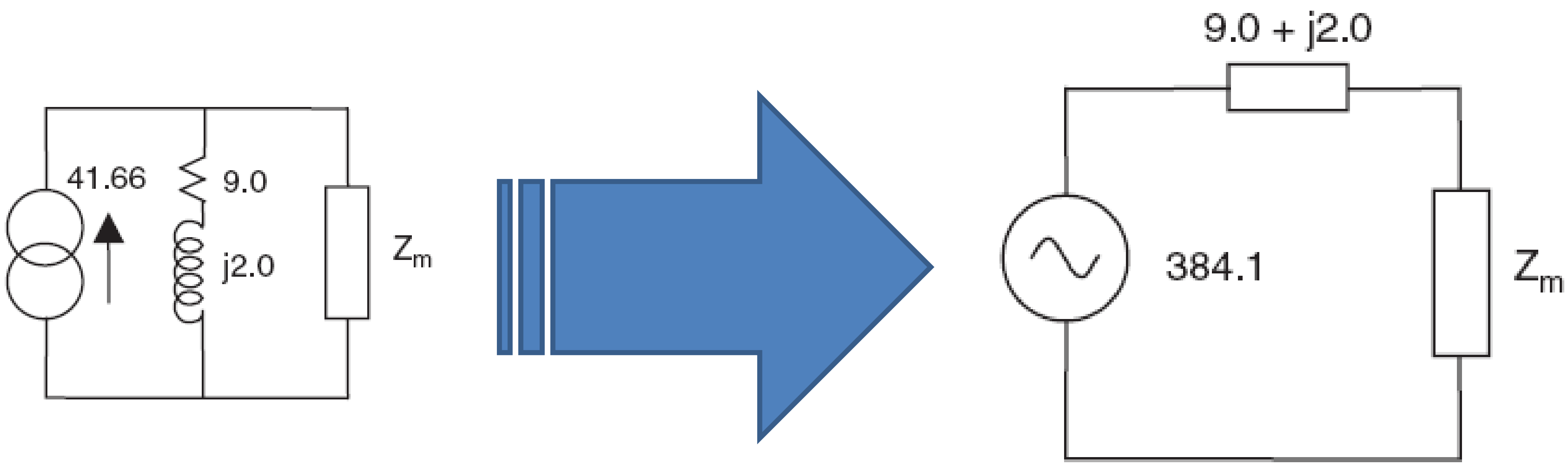
Example 2

Consider a CT of 600:5, and the magnetizing characteristic corresponding to this ratio in previous Figure. Calculate the current in its secondary winding for a primary current of 5000 A, if $\mathbf{Z_b}$ is (9 + j2) Ω and the secondary leakage impedance is negligible. The impedance angle of the magnetizing branch is 60◦.

A current source of **5000 × 5/600 = 41.66 A** in parallel with the burden, and connected across the nonlinear $\boldsymbol{Z_m}$,



The corresponding Thevenin equivalent consists of a voltage source of **41.66 × *(9 + j2)* = 384.1∠12.53◦ volts**, in series with the burden.



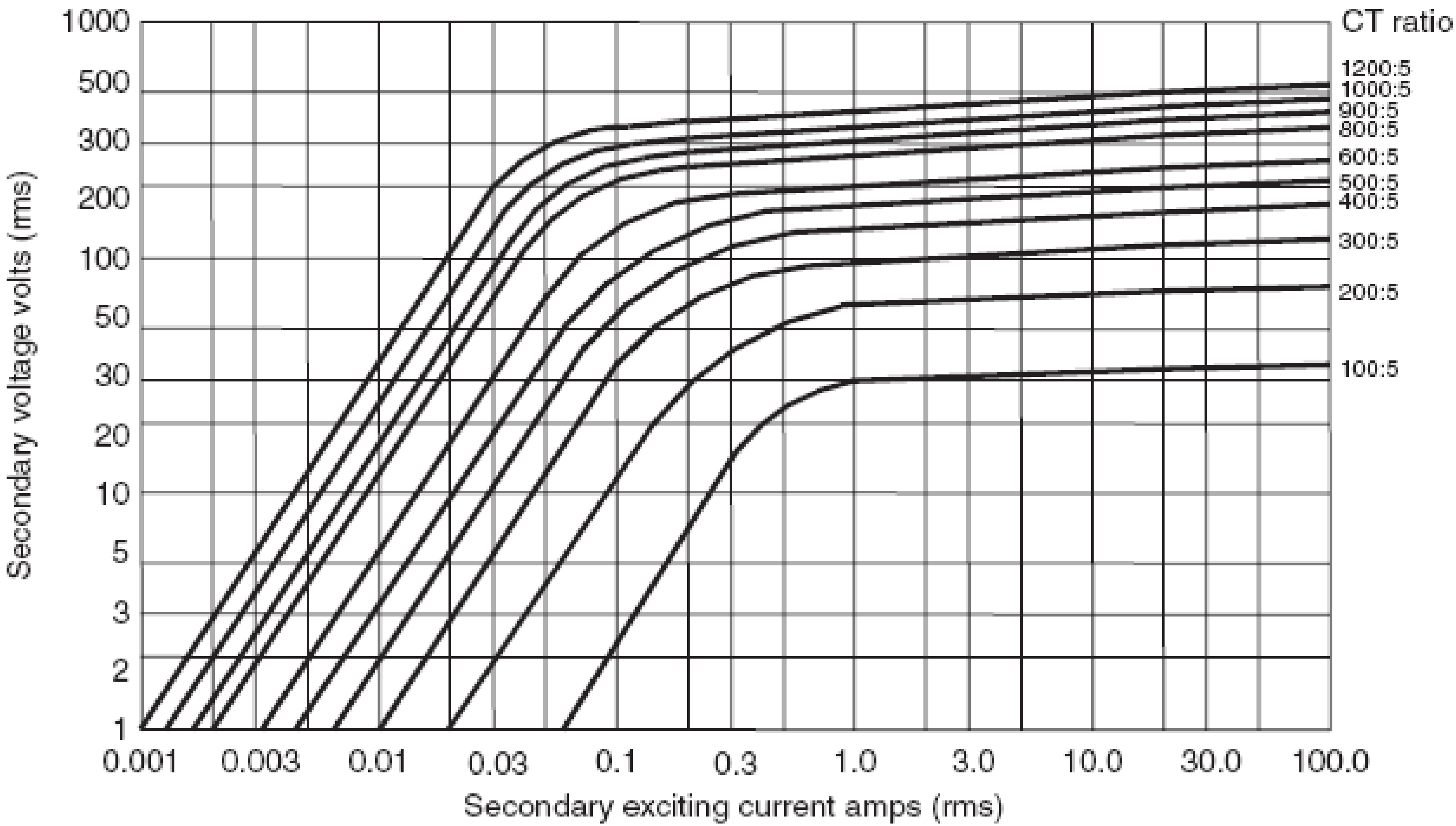
$$I_{\mathrm{m}} = \frac{384.1}{[|Z_{\mathrm{m}}| \times (0.5 + \mathrm{j}0.866) + (9.0 + \mathrm{j}2.0)]}$$

$$E_2 = I_{\mathrm{m}} Z_{\mathrm{m}}$$

These two equations may be solved to produce values of ***E_2*** and ***I_m*** in terms of **|*Z_m*|** as the parameter.

$\lvert Z_m \rvert$	$\lvert I_m \rvert$	$\lvert E_2 \rvert$
∞	0	384.1
100	3.61	361.0
10	21.82	218.2

Plotting the curve of these values on magnetization curve, it is found to intersect the magnetizing characteristic at $\boldsymbol{I_m = 17}$ A, $\boldsymbol{E_2 = 260}$ V. Finally, reworking the equations to find the phase angles of the currents, the various currents are: $\boldsymbol{I_1 = 41.66\angle 0^\circ}$ (in that case, $\boldsymbol{E_{th} = 384.1\angle 12.5^\circ}$), $\boldsymbol{I_m = 17\angle -29.96^\circ}$ and $\boldsymbol{I_z = 28.24\angle 17.5^\circ}$. The error $\boldsymbol{\varepsilon}$ is therefore $\boldsymbol{0.408\angle -29.9^\circ}$ and the ratio correction factor $\boldsymbol{R = 1.47\angle -17.5^\circ}$.



This CT is in severe saturation at this current and at the burden chosen. In practice, it must be used with much smaller burdens to provide reasonable accuracies under faulted conditions.

Standard Class Designation

It is defined by the American National Standards Institute **(ANSI)** and the Institute of Electrical and Electronics Engineers **(IEEE)**.

Designation of a CT consists of two integer parameters, separated by the letter **'C'** or **'T'**: for example, **10C400** or **10T300**.

The first integers describe the upper limit on the error made by the CT when the voltage at its secondary terminals is equal to the second integer, while the current in the transformer is 20 times its rated value.

First integers

Upper limit on the error made by the CT

Second integers

voltage at its secondary terminals (I_2 = 20 I_{NCT})

C

The CT performance can be calculated

T

Some uncertainties in the transformer design, and the performance of the CT must be determined by testing the CT.

For Example:

The **600:5**, **10C400** CT, will have an error of less than or equal to **10%** at a secondary current of **100 A** for burden impedances which produce **400 V** or less at its secondary terminals.

Example 3

Consider a 600:5 turns ratio CT of the class 10C400. Determine the maximum burden impedance if the fault current is 5000 A.

The 10C400 CT will provide 100 A in the secondary with no more than 10% error at 400 V secondary. Thus the magnitude of the magnetizing impedance is approximately $400/(0.1 \times 100) = 40\ \Omega$.

With a primary current of 5000 A, the nominal secondary current will be $5000 \times 5/600 = 41.66$ A.

With a maximum error of 10%, this will allow a magnetizing current of about 4.16 A. At this magnetizing current, it may have a maximum secondary voltage of 4.16 × 400/10, or 167 V.

Since the primary current is 41.66 A, the maximum burden impedance which will produce 167 V at the secondary is 167/(41.66 − 4.16) = 4.45 Ω. All burdens of a smaller magnitude will produce smaller errors.

we have assumed that:

1. The $\underline{\mathbf{I}_m}$ is in phase with the $\underline{\mathbf{I}_1}$ and $\underline{\mathbf{I}_2}$.
2. Linear magnetizing characteristic).

This approximation is justifiable.

Polarity markings on CT windings

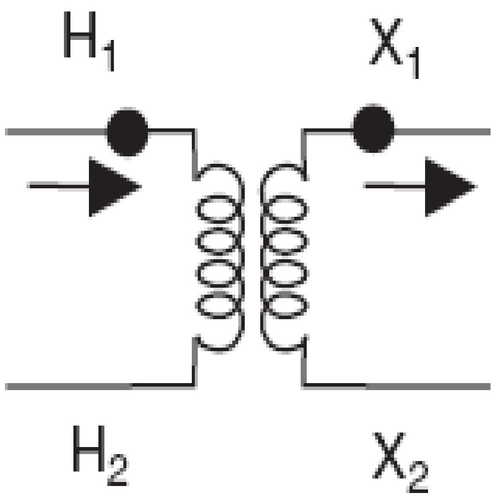
Polarity markings of transformer windings are a means of describing the relative directions in which the two windings are wound on the transformer core.

The terminals identified by solid marks indicate the starting ends of the two windings, meaning that if these are considered to be the starting points, and we trace the two windings along the transformer core, both windings will go around the core in the same sense (i.e. counterclockwise or clockwise).

In a transformer, if one of the winding currents is considered to be flowing into the marked terminal, the current in the other winding should be considered to be leaving its marked terminal.

An alternative way is to label the primary winding terminals $\underline{\mathbf{H_1}}$ and $\underline{\mathbf{H_2}}$, and the secondary winding terminals $\underline{\mathbf{X_l}}$ and $\underline{\mathbf{X_2}}$. $\mathbf{H_1}$ and $\mathbf{X_1}$ may then be assumed to have the polarity mark on them.

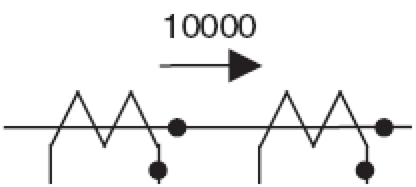
$\underline{\mathbf{I_1}}$ will produce $\underline{\mathbf{I_2}}$, where the magnitudes of $\underline{\mathbf{I_1}}$ and $\underline{\mathbf{I_2}}$ are in inverse proportion to the turns ratio, and their phase angles will be as indicated by the polarity markings.



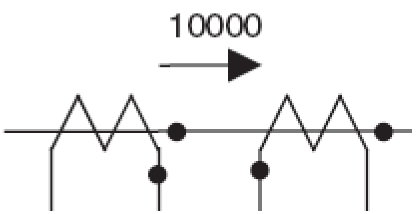
The current transformer is considered as a constant current source of *I*2 as determined by $\underline{\mathbf{I_1}}$. If $\underline{\mathbf{I_1}}$ is zero, $\underline{\mathbf{I_2}}$ also must be zero, and the secondary winding of such a CT may be considered to be open-circuited.

Example 4

If the primary current is 1000 A, and the two CT ratios are 1000 : 5. Determine the burden current for the following two cases.

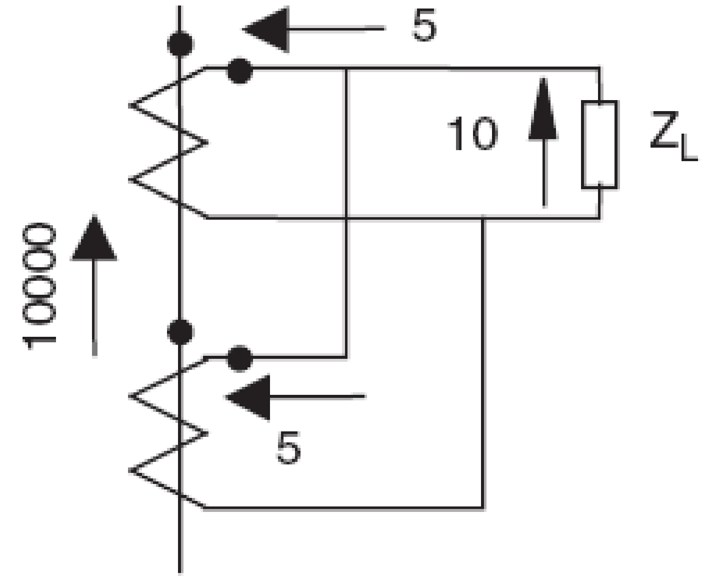


a



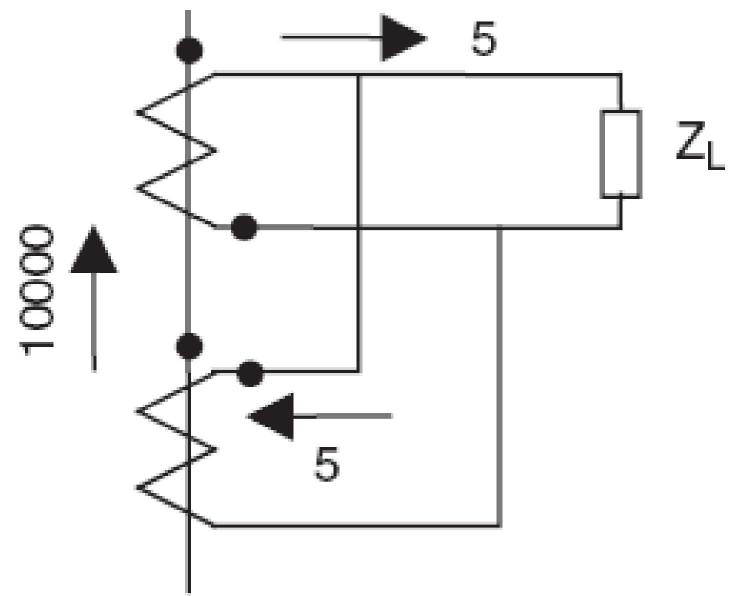
b

the current in the burden impedance $\mathbf{Z_L}$ is 10 A.



(a)

the current in the burden impedance $\mathbf{Z_L}$ is zero.



(b)

Special connections of current transformers

Auxiliary current transformers

They are used to provide an adjustment to the overall current transformation ratio.

Auxiliary CTs with multiple taps, providing a variable turns ratio, are also available.

The burden connected into the secondary winding of the auxiliary CT is reflected in the secondary of the main CT, according to the normal rules of transformation:

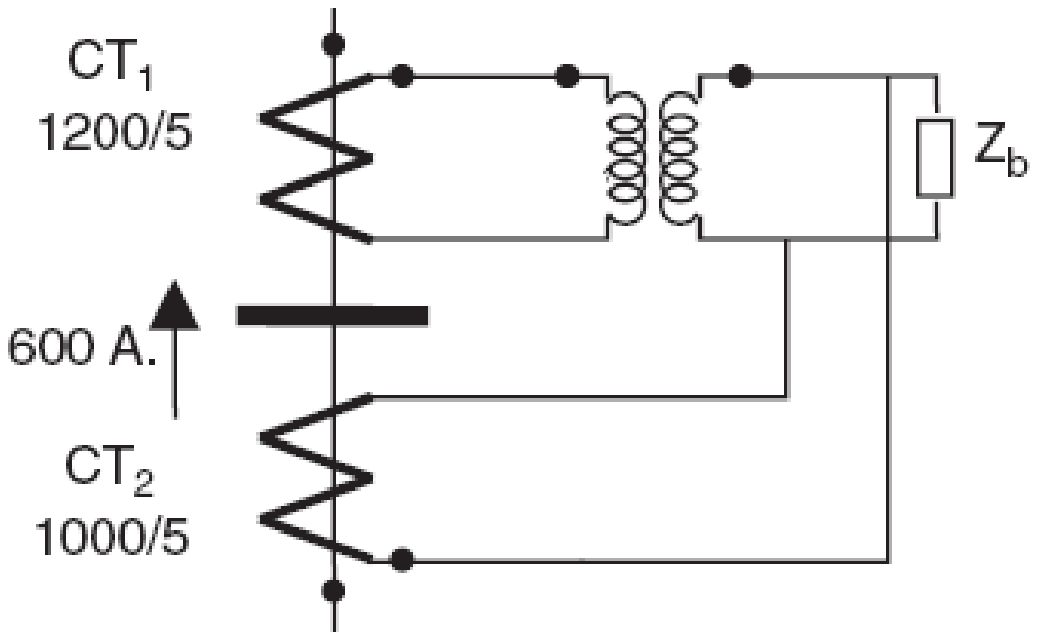
If the auxiliary CT ratio is $1 : n$, and its burden is Z_l , it is reflected in the main CT secondary as Z_l/n^2.

The auxiliary CT makes its own contributions to the overall errors of transformation.

In particular, the possibility that the auxiliary CT itself may saturate should be taken into consideration.

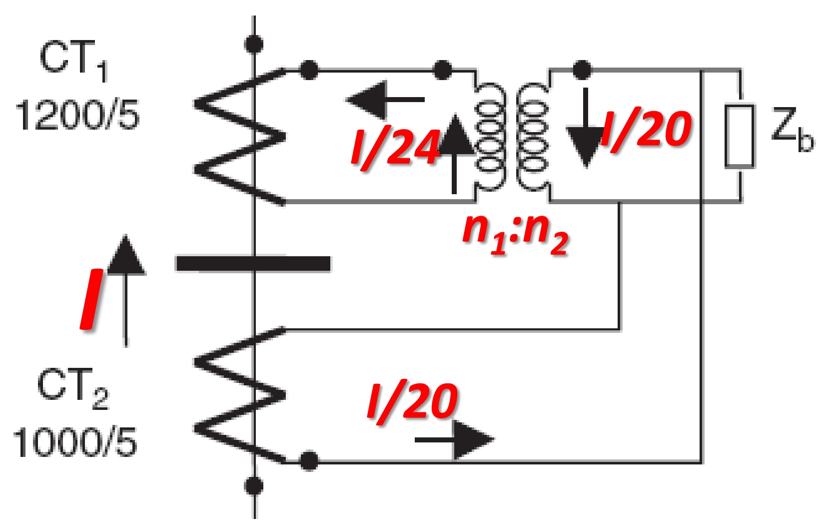
Example 5

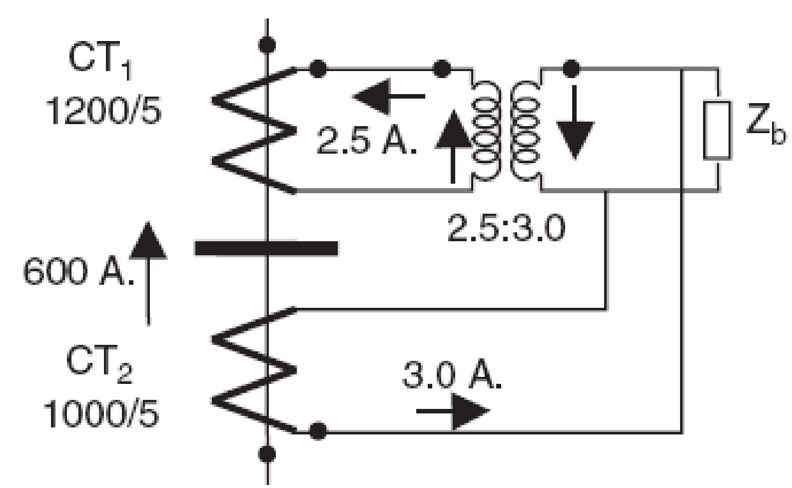
Consider the CT connection shown in Figure CT1 has a turns ratio of 1200:5, while CT2 has a turns ratio of 1000:5. Suggest what’s do to have a zero current in the burden impedance.



Assume the primary current to be ***I***. The current in the secondary winding of CT1 is **I/24** and that in the secondary winding of CT2 is **I/20**.

By inserting an auxiliary CT with a turns ratio of $\mathbf{n_1{:}n_2}$ in the secondary circuit of CT1, the current in the auxiliary CT secondary becomes **I/20**. if $\mathbf{n_1{:}n_2 = 6/5}$**.** With the polarity markings as shown, the burden current is zero.

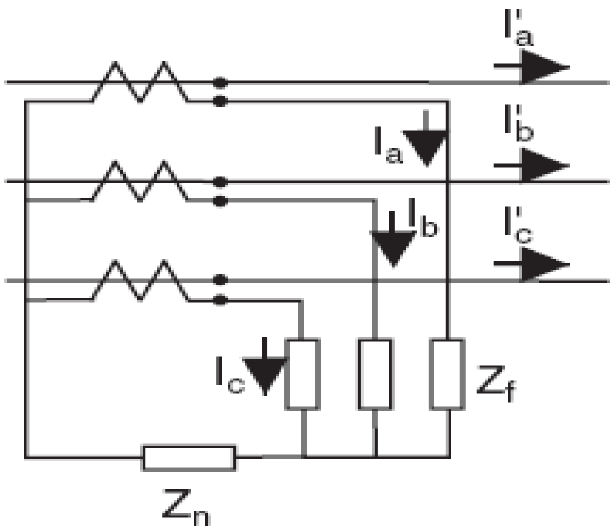


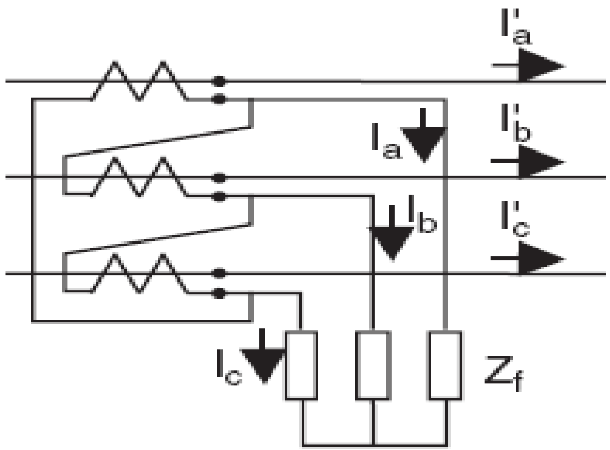


Wye and delta connections

Wye

Delta





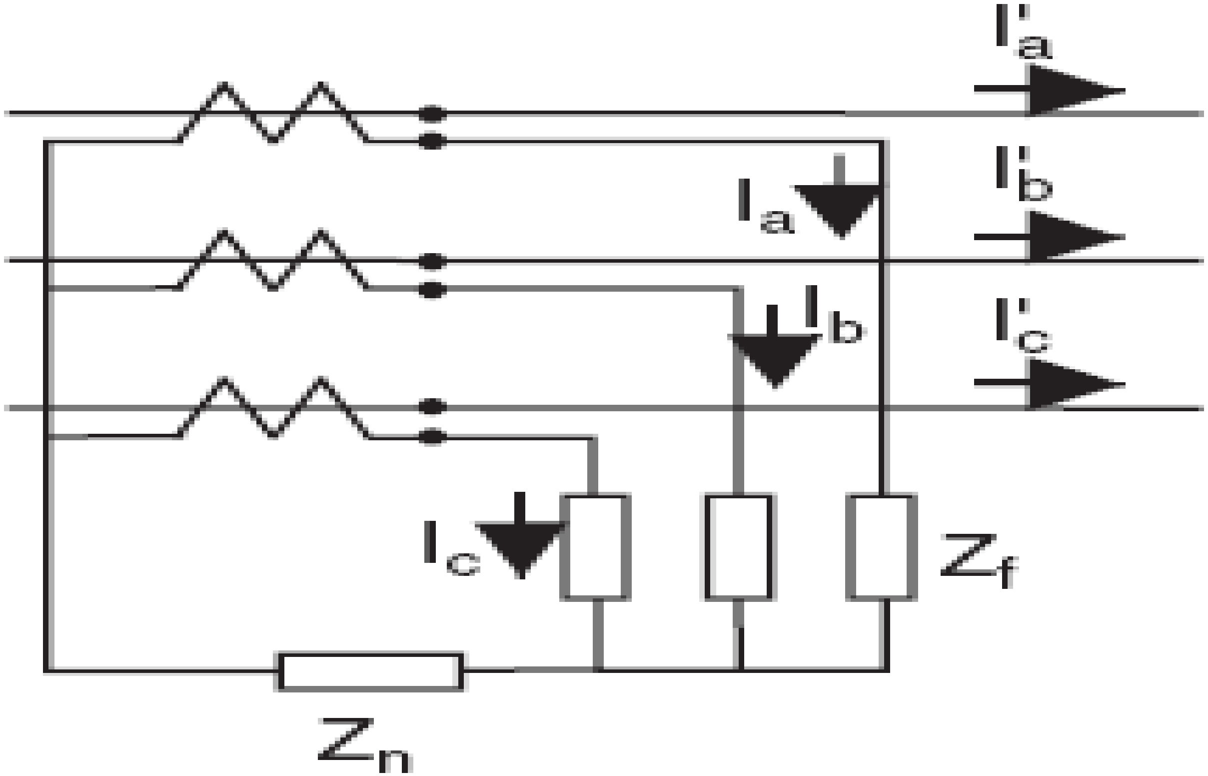
$\mathbf{I_a}$, $\mathbf{I_b}$ and $\mathbf{I_c}$ are proportional to $\mathbf{I_a}'$, $\mathbf{I_b}'$ and $\mathbf{I_c}'$. No phase shifts are introduced by this connection.

a phase shift of 30° is introduced between the primary currents and the currents supplied to the burdens.

Zero-sequence current shunts

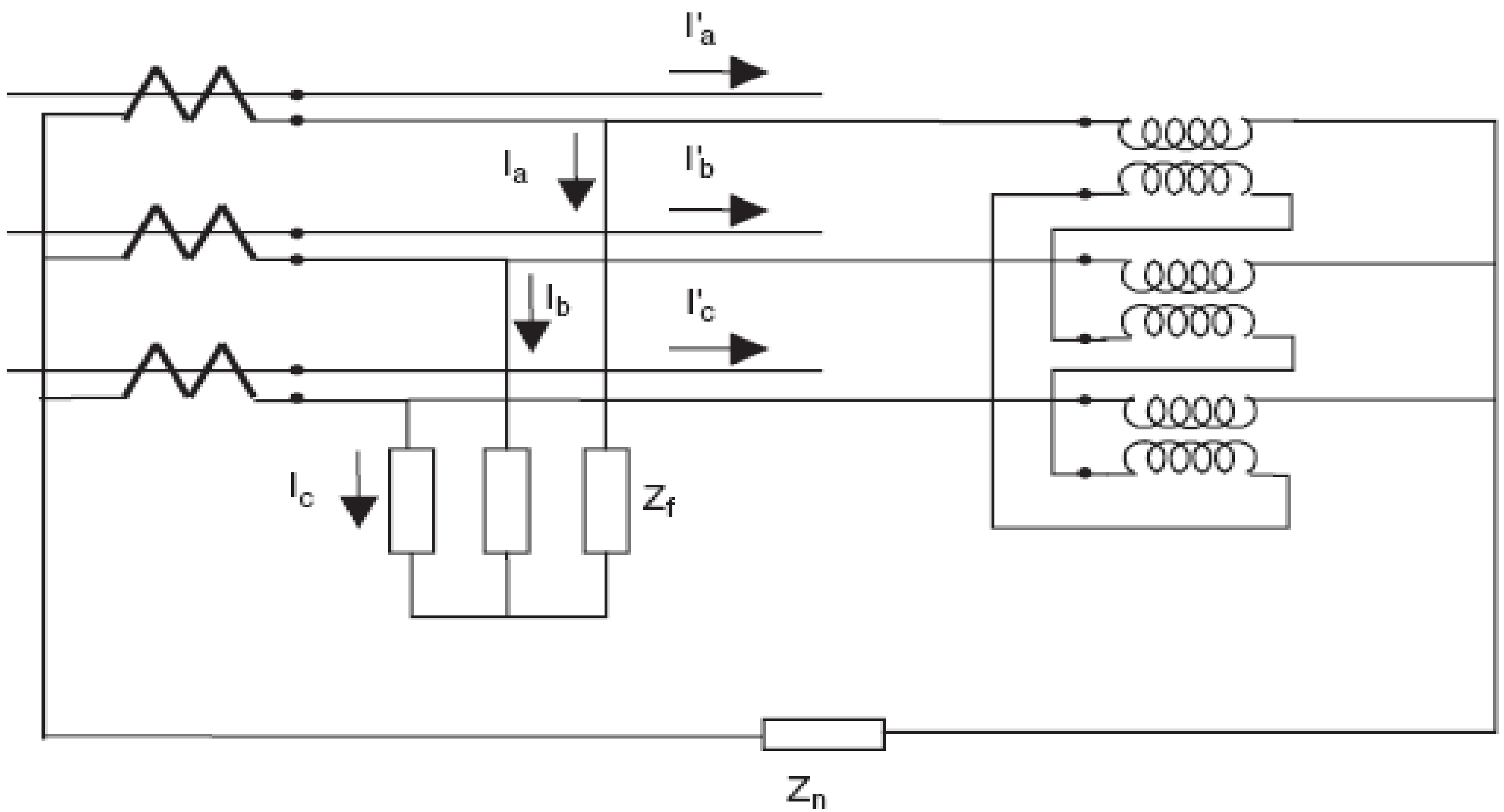
1

Each of the phase burdens Z_f carries phase currents, which include the positive, negative and zero-seq components.



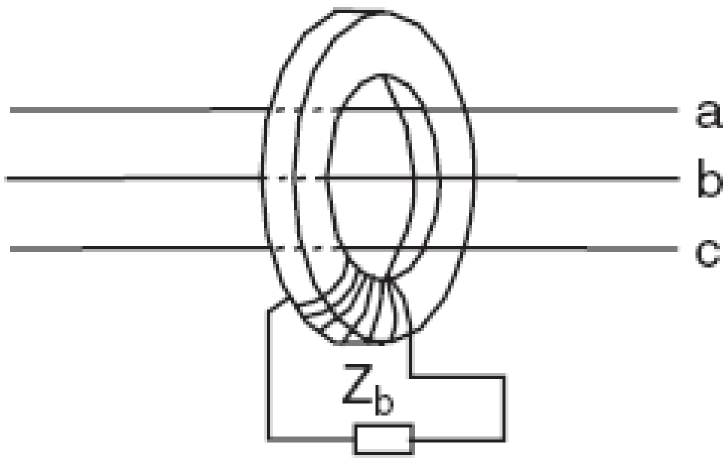
2

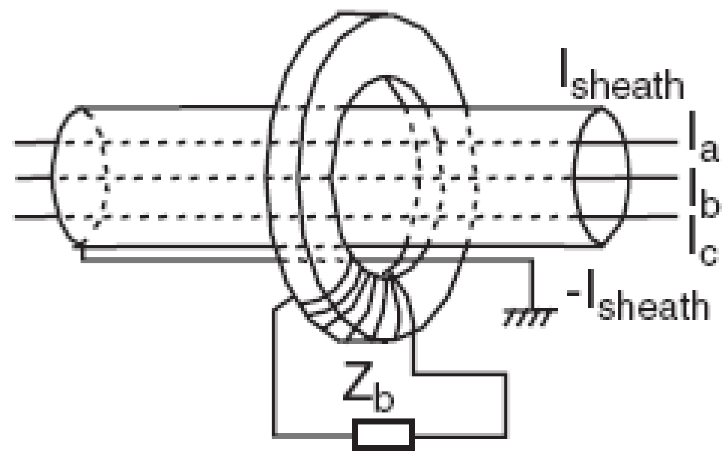
Sometimes it is desired that the zero-sequence current be bypassed from these burdens. This is achieved by connecting auxiliary CTs which provide an alternative path for the zero-sequence current.



Flux-summing CT

If three phase conductors are passed through the window of a toroidal CT, the secondary current is proportional to $\underline{\boldsymbol{(I_a+I_b+I_c)=3I_0}}$.
Since this arrangement effectively sums the flux produced by the three phase currents, the CT secondary contains the true zero-sequence current.



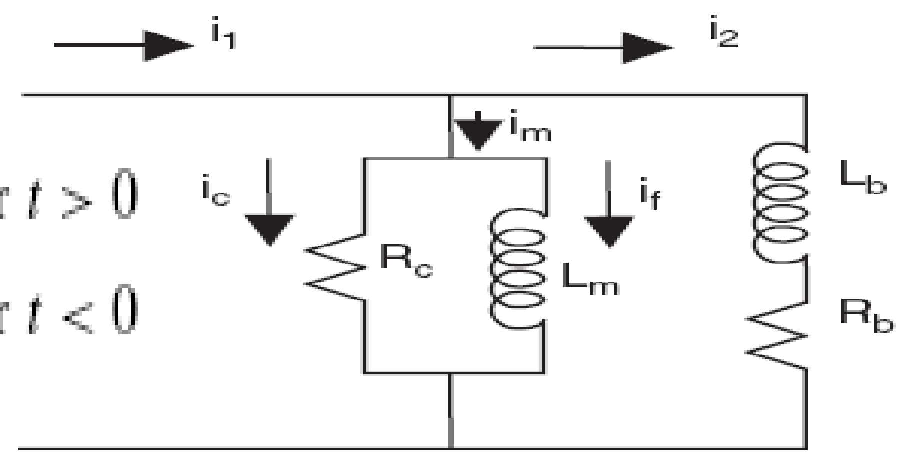


Transient performance of current transformers

When faults occur, the current magnitudes could be much larger, the fault current may have DC components and there may be remanence in the CT core. All of these factors may lead to saturation of the CT core, and cause significant distortion of the secondary current waveform.

Consider the sum of the secondary leakage impedance, lead impedance and load impedance – given by $Z_b = (R_b + j\omega L_b)$.

$$
\begin{aligned}
i_1(t) &= I_{\max}[\cos(\omega t - \theta) - \varepsilon^{-t/T} \cos\theta] \quad \text{for } t > 0 \\
&= 0 \quad \text{for } t < 0
\end{aligned}
$$



Report

Example 6

Consider a purely resistive burden of **0.5 Ω** being supplied by a CT with ***R_c*** of **100 Ω**, and ***L_m*** of **0.005 H**. Let ***i_1*** with a steady-state value of **100 A** be fully offset. Let ***τ*** be **0.1 s**. determine ***λ*** and ***$i_2(t)$***

$$i_1 = 141.4 \times \epsilon^{-10t} - 141.4\cos(\omega t)$$

$$\theta = \pi, R_c = 100, R_b = 0.5, T = 0.1 \text{ s}$$

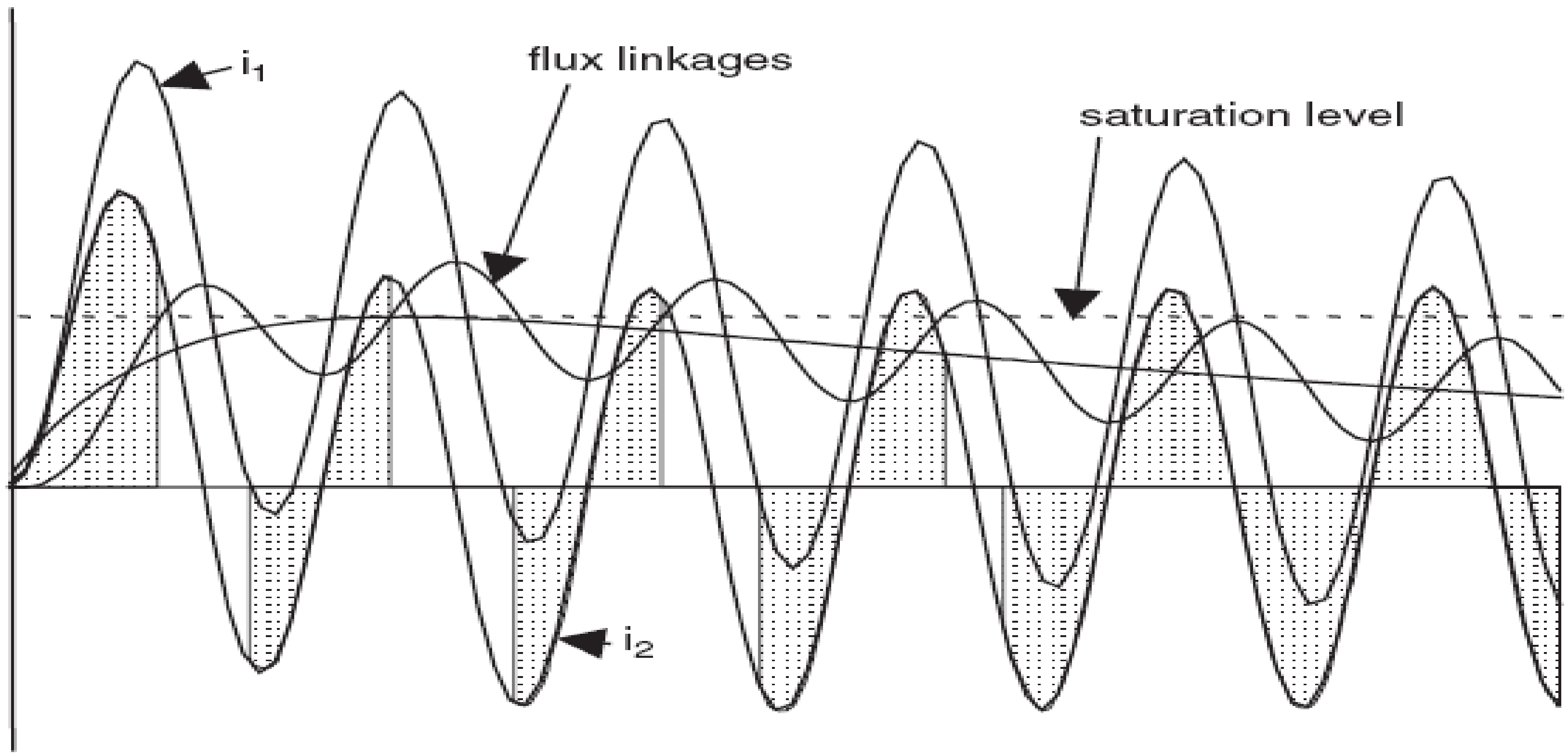
$$\tau = \frac{(100 + 0.5) \times 0.005}{100 \times 0.5} = 0.01005$$

$$\omega\tau = 377 \times 0.01005 = 3.789$$

$$\varphi = tan^{-1}(3.789) = 75.21^\circ = 1.3127 \text{ rad}$$

$$\lambda = -0.7399\varepsilon^{-99.5t} + 0.786\varepsilon^{-10t} - 0.1804\cos(\omega t - 1.3127)$$

$$i_2 = 147.24\varepsilon^{-99.5t} - 15.726\varepsilon^{-10t} + 136.02\sin(\omega t - 1.3127)$$



The DC component in the fault current causes the flux linkages to increase considerably above their steady state peak.

The dotted line represents the flux level at which the transformer core goes into saturation.

Thus, for the duration that λ is above the dotted line, it is held constant at the saturation level, and the magnetizing inductance L_m becomes zero.

the secondary current for this period also becomes zero.

I_2 of a CT may not represent I_1 faithfully if the CT goes into saturation, and hence relays which depend upon I_2 are likely to mis-operate during this period.

Conclusion

The possibility of CT saturation must be taken into account when designing a relaying system.

Linear couplers and electronic current transformers

Linear couplers are CTs without an iron core. The magnetizing reactance of these transformers is linear, and is very small compared to that of a steel-cored CT.

The linear coupler operates as a current-to-voltage converter: the voltage is a faithful reproduction of the primary current.

The transformation ratio is practically constant.

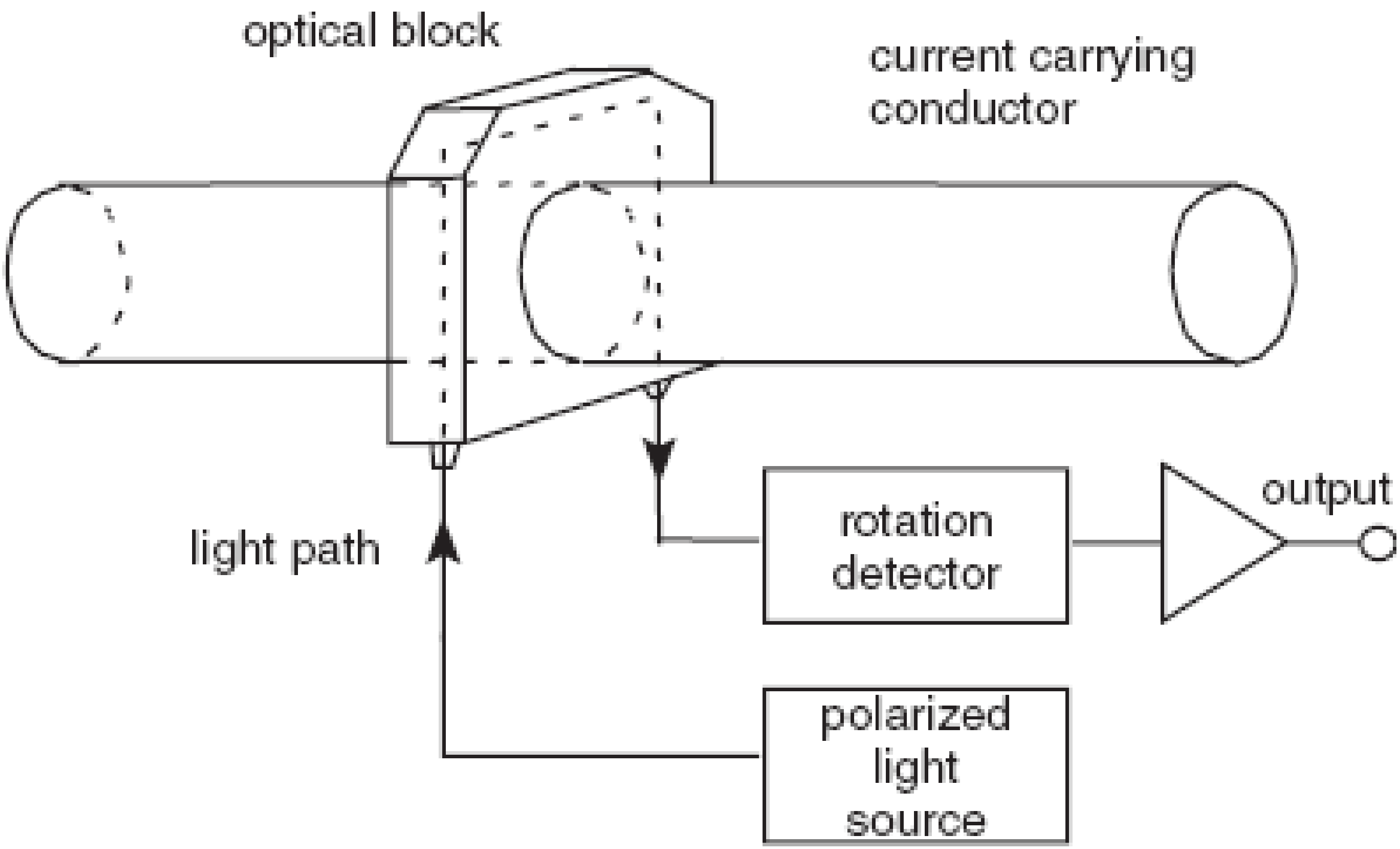
The main use of linear couplers is in applications where saturation of the CT presents a major problem (bus protection applications).

Advantages of electronic CTs

1. They are linear,
2. They have a very wide dynamic range.
3. They do not include oil as an insulating medium, they do not constitute a fire hazard.
4. They are also smaller in size and require less space in a substation.

Disadvantages of electronic CTs

1. They do require a power supply to operate
2. Various electronic circuits required to sense and amplify the signals.


optical block
current carrying
conductor
output
rotation
detector
light path
polarized
light
source

Voltage transformers

VTs are normal transformers with the primary winding connected directly to the HV, and with one or more secondary windings rated at the standard voltage of 69.3 V for LN voltages or 120 V for LL voltages.

Their performance, equivalent circuit and phasor diagrams are similar to those of a power transformer.

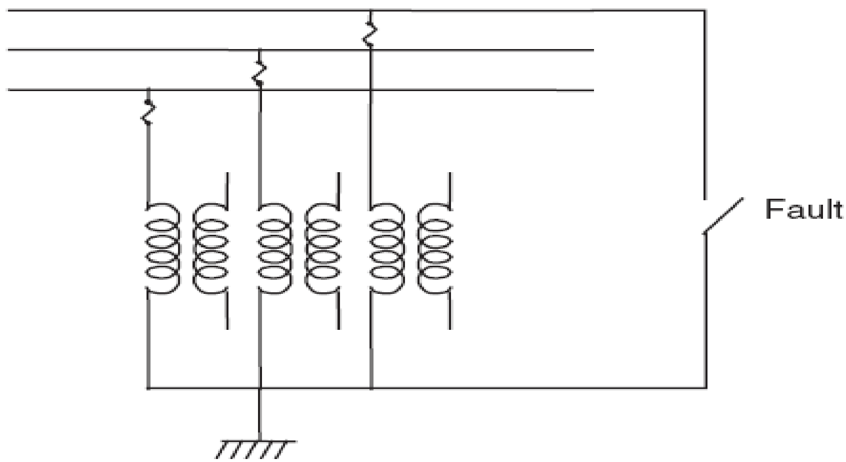
We may consider such transformers to be error-free from the point of view of relaying.

VTs are usually used for low-, medium- and high-voltage systems.

VTs are rather expensive, especially at EHV (**345 kV or above**).

At EHV, capacitive voltage transformers **CVT**, are the more usual sources for relaying and metering.

There is a problem with VTs when used on ungrounded (or high-impedance grounded) power systems.

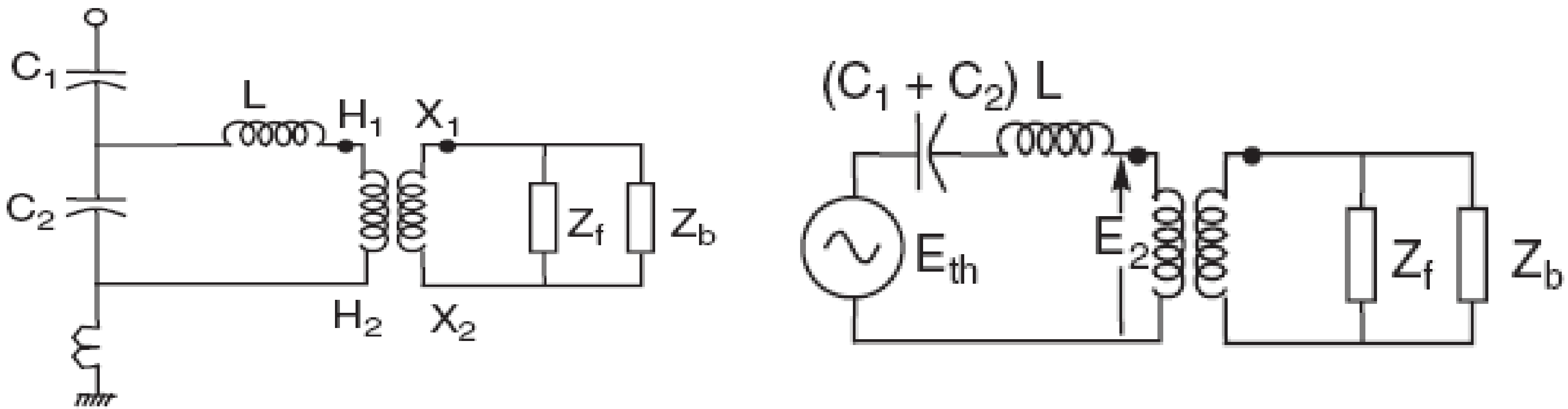


Blown fuse in a VT on ungrounded systems

When SLG occurs, the VTs connected to the unfaulted phases are subjected to a voltage equal to the LL voltage. **This drives one of VTs to be into saturation**.

Coupling Capacitor VT

String of capacitors is used as a potential divider between the HV and ground, and a tap provides a reduced voltage of about 1 to 4 kV.



The tap point is connected to a transformer through an inductance. $\mathbf{Z_b}$ is burden impedance. $\mathbf{Z_f}$ is a damping circuit for suppressing ferroresonance.

The current drawn by $\mathbf{Z_f}$ and $\mathbf{Z_b}$ is relatively small under normal conditions.

Consider the Thevenin equivalent circuit of the capacitive divider, where $E_{th} = E_{pri}C_1/(C_1 + C_2)$, and $Z_{th}\ \alpha\ (C_1 + C_2)$.

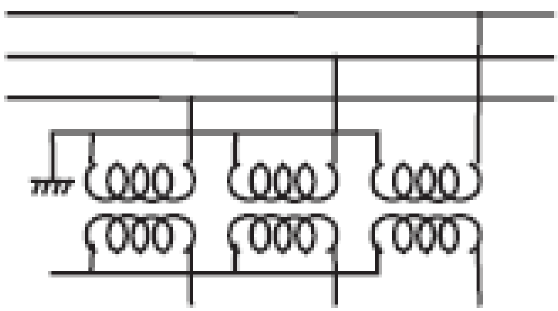
$$E_2 = E_{\mathrm{th}} - I_1\left[j\omega L + \frac{1}{j\omega(C_1 + C_2)}\right]$$

E_2 will have a phase angle error, unless the inductance L is in resonance with $(C_1 + C_2)$ at **f = 50 Hz**.

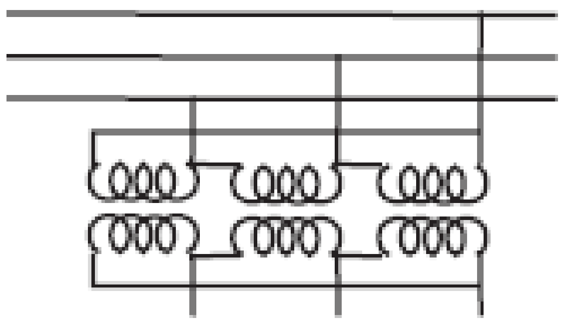
$$L = \frac{1}{\omega^2}\frac{1}{(C_1 + C_2)}$$

VTs are marked to indicate polarity. Terminals of same polarity are identified by dots, or by labels **H_1, H_2** and **X_l, X_2**.

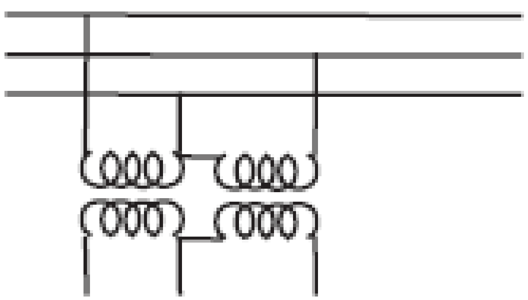
Windings of **3-Φ VTs** may be connected in **Y** , in **Δ** or in **open Δ**, as needed in each application.



Y



Δ



Open Δ

Electronic voltage transformers

Electronic voltage transformers have not been developed to the same extent as electronic current transformers.

The main difficulty arises because a voltage measurement needs a reference point, and hence both HV terminal as well as the ground terminal must be included in the measuring device.

Nevertheless, some progress in making a practical electronic voltage transformer has been made in recent years.